Int. J. Wildland Fire 3(3): 169-178, 1993

Thinning Young Loblolly Pine Stands with Fire

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Abstract. The relationship between fire-caused stem girdling and groundline diameter (GLD) in loblolly pine (*Pinus taeda* L.) was determined. Results of 10 experimental prescribed burns conducted across a wide range of ambient temperature conditions during both the dormant and growing season demonstrate that low-intensity backing fires (< 346 KW/m) are an effective tool to eliminate loblolly pines less than 3.8 cm (1.5 in.) GLD. Wide differences in ambient temperature at time of burning did not affect stem kill of unscorched trees in this study. Virtually all fire-caused mortality took place within four months postburn. A predictive model that explained 92% of the variation in mortality was developed to facilitate the use of fire to thin young, overcrowded loblolly pine stands in the southeastern United States. Use of this model in conjunction with a preburn stand survey allows estimation of the number and distribution of survivors prior to ignition.

Keywords: Fire effects; Tree mortality; Stand density control; Georgia, USA

Introduction

More acreage in the southeastern United States is managed for loblolly pine (*Pinus taeda* L.) than for any other species. Good seed years occur frequently and, when coupled with a receptive seedbed and favorable weather, result in overstocked stands commonly referred to as "dog-hair" stands. Stands exceeding 125,000 stems/ha (50,000 stems/ac) at age five are fairly common (e.g., Balmer and Williston 1973). Plantations can become overcrowded if seeds are blown in from adjacent stands.

Overly-dense stands of loblolly pine eventually thin themselves, but only after a substantial decrease in growth (Wahlenberg 1960). If wood products are a management objective, growth reduction due to intraspecific competition is generally undesirable. The higher the stand density, the sooner growth will be retarded. Haight and Smith (1991) used a dynamic programming model to demonstrate the economic advantages of thinning at an early age. Conrad et al. (1992) evaluated initial loblolly pine densities of 1,200-4,300/ha (484 to 1,742 trees/acre) at age 30 and found that wider spacings consistently produced higher economic returns. Matney and Farrar (1992) developed a simulator that allows assessment of growth and yield differences between thinned and unthinned planted loblolly stands. Work by Baldwin et al. (1989) showed selective thinning from below will result in a better growth response in overcrowded loblolly pine plantations than will row thinning.

Traditional methods to thin overcrowded stands employ machines, chemicals, or hand-labor. But, in theory, fire can produce a thinning from below at a fraction of the cost of these alternative methods. The challenge is to translate theory into operational guidelines.

Wade and Johansen (1986) provide a critical review of the literature and discussion of the variables likely to be important in fire-caused southern pine mortality. The amount and duration of energy released by a fire, flame height in relation to tree height, and the thickness and insulation properties of the bark protecting the tree bole appear to be major determinants. Plant tissue is killed when its temperature exceeds the lethal threshold, generally considered to be instantaneous at about 60°C (141°F). Total heat output of a fire is more important than peak fireline intensity in determining whether a plant's ability to dissipate a heat pulse will be overwhelmed. Residence time (the time it takes a flame zone to pass a stationary point) is thus probably a better indicator of potential basal stem damage in young southern pine stands than fireline intensity (Wade 1986).

Because heading fires have longer flames than backing fires, they result in more crown damage. However, once the base of the live crown exceeds the height of the flames, the probability of death rapidly decreases in southern pines. The higher the base of a tree crown is above ground, the greater the distance from flame tip to crown and thus the more heat required to raise the temperature of the foliage. Dense young pine stands are prime candidates for crown damage because the tightly packed foliage drastically reduces wind speed beneath the canopy, allowing flames to stand up rather than keeping them bent over. Because the base of the live pine canopy is within a few meters of the ground, there is little space below the tree crowns for the heat to dissipate and mix with cooler air before reaching the foliage. However, even complete defoliation of vigorous young loblolly pines does not result in death, unless it takes place in early fall (Weise et al. 1989), providing there is no bud damage. Whenever defoliation is accompanied by bud damage (as indicated by foliage char or consumption), mortality increases dramatically (Wade 1985). This differential mortality between needle loss and bud loss holds for multi-nodal species such as southern pines where the buds are also larger than the needles in cross section, but not for pines that have fully preformed buds, such as jack pine (*Pinus banksiana* Lamb.) and scotch pine (*Pinus sylvestris* L.); Craighead (1940) demonstrated that these two species will die if completely defoliated during the growing season.

Once crown closure occurs in dense sapling stands, herbaceous fuels quickly disappear. Pine competition often keeps other woody vegetation from becoming established. In such situations, low-intensity backing fires consume at least as much fuel as heading, surface fires, so total heat-energy release from a backing fire will at least equal that from a heading fire. Furthermore, the shorter flame envelope in backing fires concentrates heat at the base of a tree stem.

Wood acts as a heat sink so tree girth is obviously an important factor; but the thickness and insulating efficiency of the bark which covers the stem cambium is even more important. Hare (1965) related fire resistance of 14 southern tree species to bark characteristics. He found loblolly pine to be more fire-resistant than any of the southern hardwoods tested. Wahlenberg (1960) reported that suppressed loblolly pines were slow to develop thick bark. McNab (1977) measured bark thickness after a wildfire backed through a crowded loblolly pine stand and found a strong positive relationship between this variable and tree survival. Bark thickness measurements are time consuming, however, so an easily measured analog of this variable, such as groundline diameter, would be highly desirable. Work in young slash pine with no crown scorch showed basal stem diameter to be an excellent indicator of stem mortality (Johansen and Wade 1986) for that species.

Several studies have reported increased loblolly pine survival with increased stem girth (e.g., Wade 1985, Waldrop and Lloyd 1988) - the question is whether this relationship is robust enough to allow development of a useful prediction model that encompasses a wide range of conditions. Byram (1948, 1958) states the most important factor in determining crown damage is preburn vegetation temperature, which in turn depends upon ambient air temperature and direct solar radiation. Solar radiation cannot penetrate the canopy of dense young southern pine stands and thus cannot directly heat the tree boles. Ambient air temperature, on the other hand, may play an important role in determining survival of trees subjected to fire. The higher the initial fuel temperature, the less heat that is required to bring the cambium to its lethal threshold.

Research findings addressed in this paper relate survival of over 4,000 young loblolly pines to stem size and crown damage after 10 low-intensity backing fires conducted across a wide range of ambient temperatures.

Methods and Experimental Design

Nine dormant-season (winter) burns (three replications of three ambient temperature levels in a randomized block design) were conducted in dense, young (< age 8) loblolly pine stands on the Piedmont National Wildlife Refuge located on the Lower Piedmont of central Georgia, USA. A single late-summer burn conducted in a stand of the same age, and approximate size and density on the adjacent Hitchiti Experimental Forest was included in part of the analysis. The amount of fuel consumed by each fire was estimated by subtracting the average weight of six one-quarter milacre, systematically located, fuel samples taken postburn from six taken preburn. A minimum of six ocular estimates of flame length were recorded for each fire. Rate of spread was calculated by dividing the length of a plot by the time it took a fire to traverse that distance. Fireline intensity was calculated using the relationship established between flame length and fireline intensity (Nelson 1980). Residence time (the time it takes a flame zone to pass a stationary point) was visually estimated and recorded.

String lines were run through each plot within 2 weeks after each fire, and the first 700 trees with groundline diameter (GLD) larger than 0.3 cm (0.11 in.) but less than 7.6 cm (3.0 in.) and no apparent prefire defect were tagged for future reference and placed in 0.25 cm (0.10 in.) diameter classes. Height of bark char is of limited use in assessing damage in southern pines (Wade and Johansen 1986) and thus was not a criterion for selection as long as a tree occurred on burned litter. The study plan called for half of the sample trees to be free of crown damage and half to have been subjected to crown scorch between 1% and 66%, but this desire could not be attained in the field. The reason for wanting a large sample of unscorched trees was to allow two analyses of the relationship between GLD and mortality, one using both scorched and unscorched trees, and one using just unscorched trees without having to consider any confounding effects of crown scorch. Trees with foliage charred or consumed by fire were excluded from the data base. Treatment plots were resurveyed within four months after burning to assess mortality, and all plots including the unburned controls were surveyed again after the first full postfire growing season.

Regression was used to model the effects of GLD on survival. Although the test is approximate, covariance analysis was used to examine the linear regression of survival on GLD for each dormant-season treatment separately to get an idea of whether regression relationships differed among treatments.

Effects of ambient temperature on survival of unscorched trees could not be addressed through standard analysis of variance or covariance (using fireline intensity) because some diameter-class cells contained no, or few, trees and because the variance was heterogeneous. The usual arcsine transformation of percent survival did not stabilize variance among treatments. A weighted analysis was tried to solve the problem of highly variable seedling numbers used to compute proportions, but this approach created other problems. GLD class width was therefore increased from 0.25 cm (0.10 in.) to 1.3 cm (0.50 in.). Widening class range reduced the number of classes from 29 to 6 and the data were analyzed using these larger classes.

Results and Discussion

Prescribed fires

These naturally regenerated stands contained between 5,190 to 20,260/ha (2,100 and 8,200 stems/acre) (Table 1). Preburn forest-floor fuels which were comprised mainly of sloughed pine needles, weighed from 5.81 to 9.32 t/ha (2.59 to 4.16 tons/acre). Fuel consumption ranged between 2.5 and 4.9 t/ha (1.11 and 2.18 tons/acre).

The 0.16 ha (0.4 ac) plots were all burned with line backfires: Three when the ambient temperature was between 0 and 7°C (32 and 45°F) (treatment 1), three between 11 and 18°C (52 and 64°F) (treatment 2), and three between 21 and 24°C (70 and 75°F) (treatment 3) (Table 1). During the late-summer fire, ambient temperature was between 27 and 28°C (80 and 82°F) (treatment 4).

The fires burned 100% of all plots except treatment 3 replicate 2 where the relative humidity was 76% and only about 85% of the plot burned. Average flame lengths ranged from about 0.12 to 0.24 m (0.4 to 0.8 ft) on all but three burns where variable winds occasionally produced flames 0.91 to 1.22 m (3 to 4 ft) long. Rates of spread ranged between 0.27 and 0.79 m/min (0.9 to 2.6 ft/min). Mean fireline intensity was less than 346 kW/m (100 Btu/ft/s) on each fire (Table 1).

Calculated intensity of the two most intense fires was more than double that of other fires (Table 1). Both these fires were at ambient temperature treatment 2, but neither appeared to result in higher mortality within treatment 2 (Table 2). This result suggests that fireline intensity may not be a good predictor of mortality in dense young pine stands. The highest fireline intensity was, in fact, associated with the the second shortest residence time. However, mortality did

Table 1. Stand and fire characteristics.

Plot	Tree Density (Stems/ha)	Forest Floor Fuel Weight (tons/ha) Preburn	Postburn	Burn Date	Ambient Temp. Range (°C)	RH Range (%)	Flame Length (cm)[2]	Residence Time[2] (seconds)	I (KW/m)
T1 R1[1]	9,088	6.7 (2.1)[3]	3.1 (1.0)	3/15/88	5-7	28-33	18 (11)[3]	24 (08)[3]	73
T1 R2	7,126	7.8 (2.0)	4.2 (1.7)	3/15/88	0-2	42-54	12 (06)	42 (34)	28
T1 R3	12,928	7.3 (1.6)	3.4 (1.9)	3/16/88	0-5	36-51	12 (04)	42 (13)	28
T2 R1	20,284	8.4 (2.9)	4.5 (1.4)	2/09/88	16-17	24-29	49 (33)	40 (26)	173
T2 R2	6,731	8.0 (3.3)	4.1 (1.4)	2/10/88	17-18	29-30	79 (67)	29 (08)	342
T2 R3	10,232	7.5 (2.6)	4.5 (1.7)	2/09/88	11-13	29-30	18 (06)	38 (14)	28
T3 R1	12,056	9.3 (2.1)	6.0 (2.6)	2/01/88	22-24	51-53	18 (05)	38 (17)	28
T3 R2	8,028	5.8 (1.3)	2.7 (0.9)	2/02/88	21	76	18 (05)	30 (13)	28
T3 R3	6,000	7.5 (3.1)	5.0 (1.6)	2/01/88	24	51-58	24 (11)	38 (18)	48
T4 R1	5,189	7.8 (1.6)	2.7 (1.6)	9/18/89	27-28	39-43	46	- -	80

[1]T = Treatment, R = Replication
[2]Average of all observations combined (6 or more observations on each fire).
[3] First number is mean, second is standard deviation.

Table 2. Mortality of loblolly pine saplings in relation to extent of crown scorch and ambient air temperature at the time of burning.

	Unscorched Trees			1-33% Crown Scorch			34-66% Crown Scorch			67-94% Crown Scorch		
Plot	No.	% Dead	Mean GLD <7.6 cm	No.	% Dead	Mean GLD <7.6 cm	No.	% Dead	Mean GLD <7.6 cm	No.	% Dead	Mean GLD <7.6 cm
T1 R1[1]	410	48	2.8	110	65	2.5	69	61	2.8			
T1 R2	384	30	2.5	9	78	1.8	4	100	1.5			
T1 R3	475	26	2.8	8	12	3.0	5	40	2.5			
Sum/x[2]	1269	35	2.8	127	52	2.5	78	67	2.3			
T2 R1	504	27	3.3	91	23	3.8	105	30	3.6			
T2 R2	160	09	4.6	37	16	4.3	53	37	3.8	7	0	5.8
T2 R3	386	20	3.6	98	34	3.3	100	41	2.8			
Sum/x	1050	19	3.8	226	24	3.6	258	36	3.3	7	0	5.8
T3 R1	354	23	3.8	70	48	3.0	76	55	2.8			
T3 R2	349	15	4.1	132	34	3.6	115	54	2.8	59	63	2.8
T3 R3	55	13	4.6	60	27	4.1	114	49	3.8	149	59	2.5
Sum/x	758	17	4.1	262	36	3.6	305	53	3.0	208	61	2.8
T4	31	100	2.8	189	15	4.1	201	30	3.8	207	69	3.0

[1] T = Treatment, R = Replication
[2] Number of stems / mean% and GLD.

not appear to be clearly associated with residence time either. Average residence times ranged between 24 and 42 seconds on the nine fires where measurements were taken.

The number of trees actually selected on each plot ranged from 250 to 700 (Table 2), primarily because some plots tended to have more trees larger than 7.6 cm (3.0 in.) GLD due to the interaction between microsite, seedling establishment and subsequent growth. Fewer than 100 unscorched trees were found on two plots, so trees with higher levels of crown scorch (but no crown consumption) were also included on those plots. All measurement trees were allocated to one of six crown scorch classes (none, 1-33%, 34-66%, 67-94%, 95-99%, or 100%) (Table 3).

Mortality

Unburned control plots were checked for natural mortality during the final survey. Although a few dead trees were noted, none were found with a GLD larger than the threshold value of 0.3 cm (0.11 in.). Thus all mortality on the treatment plots was assumed to result from the fires.

It has been the author's experience that direct fire-caused mortality of young southern pines almost always occurs within the first year after burning, and this proved to be the case on these burns. A few additional trees died between the first and last survey, virtually all with signs of insect damage. No signs of secondary pests, such as bark beetles, were noted on the live trees during the final survey. Few trees between 5.1 and 7.6 cm (2.0 and 3.0 in.) GLD occurred on treatment 1 plots, so the mean GLD was less on these plots. This fact may explain the higher mean mortality associated with Treatment 1 trees across all scorch levels (Table 2).

The total number of trees and percent mortality by scorch class and GLD class for the four treatments (replications combined) are given in Table 3. The fires killed all stems less than 0.8 cm (0.31 in.) GLD and spared most stems larger than 5.1 cm (2.0 in.) GLD.

Model development

Several models were tested to predict survival of unscorched trees as a function of GLD. First, linear and quadratic regressions were developed by treatment. The summer burn did not yield enough unscorched trees to warrant inclusion. Results of covariance analysis using these individual treatment models suggest that ambient temperatures associated with dormant-season fires had no effect on mortality.

Next, a single quadratic regression pooling data over treatments was tried. This model produced a good fit, explaining 90% of the variability in mortality. However, the model illogically underpredicted tree survival with large values of GLD. Therefore SAS procedure NLIN (SAS Institute Inc. 1985) was used to fit a nonlinear regression equation utilizing the Mitscherlich function (Snedecor 1968). The upper asymptote was set at 1.0 to represent 100% survival. This model explained 92% of the variation in survival but depressed the curve at high values of GLD because of its asymptotic characteristics. Setting the upper limit at 1.1 corrected the problem and produced a higher coefficient of determination, but is illogical because 100% survival is the maximum that can be achieved.

Table 3. Fire induced mortality in loblolly pine by crown scorch and groundline diameter (GLD).

0% Crown Scorch	Treatment 1		Treatment 2		Treatment 3		Treatment 4	
GLD Class	% Dead	Total No.	% Dead	Total No.	% Dead	Total No.	% Dead	Total No.
0.28 - 1.27 cm	87%	(93)	83%	(23)	91%	(11)		
1.30 - 2.54 cm	58%	(478)	67%	(212)	69%	(125)	0%	(18)
2.56 - 3.81 cm	13%	(479)	15%	(390)	16%	(253)	0%	(5)
3.84 - 5.08 cm	07%	(210)	03%	(306)	03%	(205)	0%	(5)
5.11 - 6.35 cm	0%	(4)	01%	(101)	0%	(107)	0%	(2)
6.38 - 7.62 cm			0%	(18)	0%	(57)	0%	(1)
01 - 33% Crown Scorch	Treatment 1		Treatment 2		Treatment 3		Treatment 4	
GLD Class	% Dead	Total No.	% Dead	Total No.	% Dead	Total No.	% Dead	Total No.
0.28 - 1.27 cm	100%	(14)	100%	(11)	92%	(13)		
1.30 - 2.54 cm	85%	(59)	76%	(38)	75%	(68)	22%	(36)
2.56 - 3.81 cm	37%	(30)	19%	(84)	33%	(85)	23%	(47)
3.84 - 5.08 cm	17%	(23)	03%	(71)	08%	(48)	12%	(52)
5.11 - 6.35 cm	0%	(1)	0%	(20)	0%	(27)	10%	(41)
6.38 - 7.62 cm			0%	(2)	0%	(21)	0%	(13)
34 -66% Crown Scorch	Treatment 1		Treatment 2		Treatment 3		Treatment 4	
GLD Class	% Dead	Total No.	% Dead	Total No.	% Dead	Total No.	% Dead	Total No.
0.28 - 1.27 cm	100%	(9)	100%	(13)	100%	(30)	100%	(1)
1.30 - 2.54 cm	88%	(34)	76%	(70)	80%	(92)	84%	(32)
2.56 - 3.81 cm	32%	(19)	27%	(88)	40%	(89)	30%	(82)
3.84 - 5.08 cm	25%	(12)	06%	(65)	11%	(53)	15%	(47)
5.11 - 6.35 cm	0%	(4)	09%	(22)	0%	(25)	0%	(28)
6.38 - 7.62 cm					12%	(16)	0%	(11)
67 - 94% Crown Scorch	Treatment 1		Treatment 2		Treatment 3		Treatment 4	
GLD Class	% Dead	Total No.	% Dead	Total No.	% Dead	Total No.	% Dead	Total No.
0.28 - 1.27 cm					100%	(8)	100%	(3)
1.30 - 2.54 cm					92%	(52)	95%	(81)
2.56 - 3.81 cm			0%	(1)	59%	(42)	73%	(74)
3.84 - 5.08 cm					29%	(24)	20%	(35)
5.11 - 6.35 cm			0%	(4)	0%	(11)	09%	(11)
6.38 - 7.62 cm			0%	(2)	0%	(15)	0%	(3)
95 - 99% Crown Scorch	Treatment 1		Treatment 2		Treatment 3		Treatment 4	
GLD Class	% Dead	Total No.	% Dead	Total No.	% Dead	Total No.	% Dead	Total No.
0.28 - 1.27 cm							100%	(2)
1.30 - 2.54 cm							94%	(78)
2.56 - 3.81 cm							89%	(88)
3.84 - 5.08 cm							73%	(30)
5.11 - 6.35 cm							100%	(3)
6.38 - 7.62 cm								
100% Crown Scorch	Treatment 1		Treatment 2		Treatment 3		Treatment	
GLD Class	% Dead	Total No.	% Dead	Total No.	% Dead	Total No.	% Dead	Total No.
0.28 - 1.27 cm							100%	(4)
1.30 - 2.54 cm							100%	(99)
2.56 - 3.81 cm							100%	(81)
3.84 - 5.08 cm							100%	(5)
5.11 - 6.35 cm							100%	(4)
6.38 - 7.62 cm								

A segmented polynomial utilizing a second-degree polynomial to describe the data up to a GLD of 5.4 cm (2.12 in.) and a linear model beyond that point gave an accurate representation of the data base but is needlessly complicated. The model could be simplified by just using that portion of the data set between 0.8-5.4 cm (0.31 and 2.12 in.) GLD where mortality or survival were in question. This model predicts 10% and 90% survival GLD thresholds at 1.1 and 3.9 cm (0.43 and 1.52 in.), respectively. The 90% survival threshold using this model occurred at the same GLD reported by McNab (1977) for a low-intensity wildfire that backed through a loblolly pine stand. Wade (1985) assessed 31 young loblolly pine plantations after wildfires and found survival of trees larger than 4.1 cm (1.6 in.) GLD was above 90% when crown scorch was less than 75%. Waldrop and Lloyd (1988) noted similar responses when dbh exceeded 2.0 cm (0.8 in.) but they did not measure GLD's. Johansen and Wade (1986) determined that 3.8 cm (1.5 in.) GLD is a good survival threshold for slash pine (*Pinus elliotti* Engelm.) as well.

However, because a major objective of the study was to develop a prediction model useful for other fires, I chose the nonlinear asymtotic regression mentioned earlier even though it was more conservative. This model predicts 10% survival at a GLD of 1.0 cm (0.38 in.) and 90% survival at a GLD of 4.4 cm (1.75 in.). The equation is:

Prob. survival = 1- (1.84066)*(0.19101)**(GLD/2.54)
if GLD is greater than 0.94 cm (0.37 in.)
= 0 otherwise.

The points used to fit the model, the equation in SI units, and a plot of predicted values are shown in Figure 1.

Trees without crown scorch

Looking at the 3,103 trees that comprise the 0% crown scorch class (Table 3), one can see that dormant-season fires stem-killed at least 83% of the trees less than 1.3 cm (0.51 in.) but less than 07% of the trees larger than 3.8 cm (1.50 in.). Including trees less than 0.3 cm (0.11 in.) GLD to enlarge and equalize the diameter range within the smallest class to 0.03-1.3 cm (0.01-0.50 in.) would increase the percent mortality associated with this cell because all such stems were killed by the fires. Differences in percent survival among dormant-season treatments within diameter classes were generally less than 5% (maximum 11%). This result supports the covariance analysis conclusion that mortality of unscorched loblolly saplings did not differ among the ambient temperature levels tested in this study.

This finding is troubling. As ambient temperature increases, the amount of heat energy a fire must

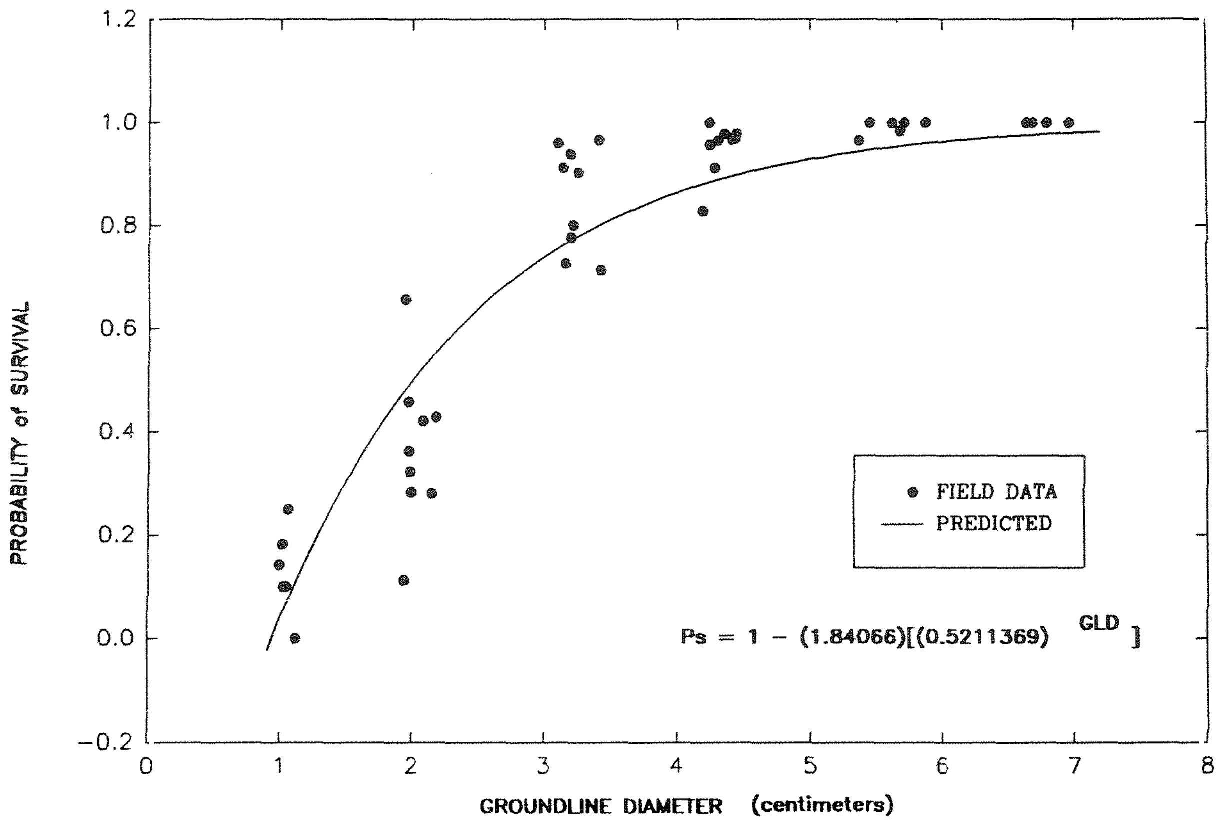

Figure 1. PREDICTED LOBLOLLY PINE SURVIVAL FROM BASAL DIAMETER.

Figure 1. Predicted loblolly pine survival from basal diameter.

provide to reach the lethal plant tissue threshold declines. It should follow that the size of trees killed will increase with increases in ambient temperature if energy release from fires is held constant. Because the presence of bark char was not a prerequisite for selection and recorded flame lengths were as low as 0.06 m (0.2 ft), some stems may in fact not have been subjected to measurable heat stress even though the forest floor surrounding the bole was blackened. Or perhaps the heat release from even these low-intensity fires was large enough to override the effect of ambient temperature differences. I don't think the fact that these suppressed trees may have had thin bark was the only reason, because if so, there should not have been unequal mortality between seasons.

None of the 31 unscorched trees in the late-summer treatment died (Table 3). This result was unexpected because up to 69% of the unscorched dormant-season-fire trees in the same diameter classes died. Increased summer survival may be due, at least in part, to higher bark moisture content during the growing season. Although not confirmed in southern pine, one southern species where this relationship was studied, *Liriodendron tulipifera* L., had significantly higher bark moisture content during the summer than in the winter (Phillips and Schroeder 1973). Martin (1963) reported that thermal conductivity and specific heat of bark increase with increased moisture content but that moisture has little affect on thermal diffusivity. As crown scorch increases, the mitigating influence of increased bark moisture content during the growing season becomes less important. It is possible, but in my estimation highly unlikely, that the stems were girdled, and phloem connections reestablished in time to prevent death. Although this possibility was not specifically addressed in the present study, visual indicators of callus growth were not observed. Work by Greene and Shilling (1987) showed cell division in loblolly pines less than 10 cm (4 in.) GLD was not fast enough for callus tissue to bridge stem girdles caused by a propane-fueled fire simulator.

All trees

Inspection of the full data set including trees with crown damage reveals that, as expected, highest mortality is associated with greatest crown scorch. Measurement trees that exhibited complete crown scorch but no crown consumption were only recorded after the September 18th fire. All 193 trees with 100% crown scorch in the late-summer treatment died irrespective of diameter. This finding agrees with results of a study conducted to assess the relationship between crown defoliation and season of treatment on young loblolly pines (Weise et al. 1989).

Table 4 was produced by combining treatment data in each of the first four crown scorch classes. Percent mortality increased as crown scorch increased, except in the two largest GLD classes, where the number of measurement trees in the affected cells was small. Virtually all trees less than 1.3 cm (0.51 in.) GLD succumbed if they exhibited even a small amount of crown scorch.

The ability to preselect burning conditions to produce a given crown scorch height would allow prescribed burners to decide what size trees to put under various levels of stress. Tables based on an equation developed by Van Wagner (1973) that predicts crown scorch height prior to ignition are given in the fire behavior prediction system BEHAVE (Andrews and Chase 1989). Burrows et al. (1989) developed a model to predict scorch height from fireline intensity and found it predicted a higher scorch height for a given intensity in comparison to Van Wagners equation. They attribute this difference to the significant amount of coarse woody fuels (tops, limbs and logs) consumed in their fires which were conducted in radiata pine (*Pinus radiata* D. Don) plantations. Large woody debris is not taken into account in Byrams fireline intensity equation. Since the validity of Van Wagner's relationship for use in southern pine has yet to be demonstrated, I recommend one not use the BEHAVE tables, especially in young stands where small differences in scorch height can have major consequences.

Table 4. Fire induced mortality in loblolly pine by crown scorch and groundline diameter (all treatments combined).

	0% Scorch		01 - 33% CS		34 - 66% CS		67 - 94% CS	
GLD Class	% Dead	Total No.	% Dead	Total No.	% Dead	Total No.	% Dead	Total No.
0.28 - 1.27 cm	87(+06)[1]	127	97(+07)	38	100	53	100	11
1.30 - 2.54 cm	61(+03)	833	69(+06)	201	81(+05)	228	94(+04)	133
2.56 - 3.81 cm	14(+02)	1127	27(+05)	246	33(+05)	278	68(+08)	117
3.84 - 5.08 cm	04(+01)	726	08(+04)	194	11(+04)	177	24(+11)	59
5.11 - 6.35 cm	0	214	05(+05)	89	03(+04)	79	04(+09)	26
6.38 - 7.62 cm	0	76	0	36	07(+11)	27	0	20

[1] = Percent mortality (95% confidence limit).

Table 5. Fire induced mortality in loblolly pine by treatment and groundline diameter (crown scorch classes combined).

GLD Class	Treatment 1 SC 1-3 % Dead	Treatment 1 SC 1-3 Total No.	Treatment 2 SC 1-3 % Dead	Treatment 2 SC 1-3 Total No.	Treatment 3 SC 1-3 % Dead	Treatment 3 SC 1-3 Total No.	Treatment 4 SC 1-3 % Dead	Treatment 4 SC 1-3 Total No.	Treatment 4 SC 1-5 % Dead	Treatment 4 SC 1-5 Total No.
0.28 - 1.27 cm	90(+06)[1]	116	91(+09)	47	96(+06)	54	100	1	100	6
1.30 - 2.54 cm	63(+03)	571	70(+05)	320	74(+05)	285	41(+10)	86	76(+05)	245
2.56 - 3.81 cm	15(+03)	528	17(+02)	562	25(+04)	427	27(+07)	134	57(+05)	296
3.84 - 5.08 cm	09(+03)	245	03(+01)	442	05(+02)	306	12(+06)	104	25(+06)	169
5.11 - 6.35 cm	0	9	02(+03)	143	0	159	06(+06)	71	09(+06)	85
6.38 - 7.62 cm	0	0	0	20	02(+03)	94	0	25	0	28

[1] = Percent mortality (95% confidence limit).

Crown scorch data within treatments are combined in Table 5. The treatment 4 data base is presented twice in Table 5: 1) using just trees in scorch classes 1-3 to make it comparable with other treatments, and 2) including all trees except those in scorch class 6 (complete defoliation). Over 90% of the 223 loblolly pines smaller than 1.3 cm (0.51 in.) GLD died irrespective of ambient temperature at the time fire treatments were applied. Inspection of Table 5 shows that percent mortality increased as ambient temperature increased following dormant season burns in the three smallest size classes. However, because most confidence intervals overlapped, the statistics used do not substantiate this visually apparent trend.

When all data were combined within GLD classes (Table 6), 95% of the 1,618 trees larger than 3.8 cm (1.50 in.) GLD survived and 98% of the 521 trees larger than 5.1 cm (2.0 in.) survived. These figures agree with results of a study conducted in Louisiana that used simulated fires (Greene and Shilling 1987). They determined loblolly pine stands with trees at least 5 cm (2 in.) GLD could be safely burned if fireline intensity was less than 100 kW/m (29 Btu/ft-sec) and severe crown scorch avoided.

Firing Technique

Only backing fires were used in this study. Although they take longer to conduct and are thus more expensive, they are less likely to consume tree crowns and thus should be preferred under most circumstances when using fire to thin overstocked young pine stands. One does not want small tree crowns to burn because they are likely to act as ladder fuels allowing flames to severely scorch, if not ignite the crowns of intended crop trees. Summer headfires, in particular, should be avoided in young stands unless the objective is to eradicate the pine understory, such as for habitat improvement around red-cockaded woodpecker (*Picoides borealis*) cavity trees.

Wind-driven wildfires sometimes race through a young stand prior to crown closure, killing just the smallest trees, but the burning window under which this happens is narrow and beyond our present capabilities to prescribe with confidence. Moreover, inspection of such stands often reveals bud damage and cambial kill on the lee side of the survivors (e.g., DeCoste et al. 1968). High levels of crown scorch temporarily retard loblolly pine growth (Wade and Johansen 1986, Waldrop and Lloyd 1988, Weise et al. 1989). Although managers might be willing to accept reduced postfire growth for a year or two to achieve a low-cost thinning from below, I recommend minimizing this possibility by using backing fires under strong persistent winds.

Table 6. Fire induced mortality in loblolly pine by groundline diameter (all treatment and crown scorch classes 1-3 combined).

GLD Class	% Dead	Total No.
0.28 - 1.27 cm	91	218
1.30 - 2.54 cm	66	1262
2.56 - 3.81 cm	19	1651
3.84 - 5.08 cm	06	1097
5.11 - 6.35 cm	02	382
6.38 - 7.62 cm	01	139

Conclusions

Ten experimental burns (nine dormant season and one late-growing season) were conducted to test the operational potential of thinning dense young loblolly pine stands with fire. Over 5,000 trees between 0.3 cm (0.11 in.) and 7.6 cm (3.0 in.) GLD were assessed. Virtually all 1,642 trees that died following these 10 fires did so within the first four months postburn.

Burns were conducted across a 28°C (50°F) range of temperatures. Although percent mortality in the smallest three size classes increased as ambient temperature increased following dormant-season burns, this trend was not substantiated by statistics because confidence intervals overlapped. This lack of effect was unanticipated and will require further study. However, this result also simplified model building to predict mortality. A nonlinear asymtotic model was fitted to the 3,100 trees in the zero-scorch dormant-season data base which explained 92% of the variation in mortality. It predicted 90% mortality and 90% survival GLD thresholds of 1.1 cm (0.43 in.) and 4.5 cm (0.76 in.), respectively. Including trees with crown scorch had little effect on these thresholds.

Survival of trees following the late growing-season burn differed dramatically from that following winter burns. Up to 69% of the unscorched trees in diameter classes larger than 1.3 cm (0.50 in.) GLD died in the dormant-season fires, whereas all trees that escaped the mid-September fire without crown damage survived. On the other hand, trees subjected to the late growing-season fire that exhibited complete crown scorch and no apparent bud damage all died. This suggests that the boles of physiologically active loblolly pine may be more resistant to late-growing season fire but that their crowns are not. Results of this study demonstrate that low-intensity (< 346 KW/m) backing fires can produce a thinning from below where the GLD range in over-stocked loblolly pine stands is wide enough to allow differential survival and where the trees targeted for removal have GLD's less than 3.8 cm (1.50 in.). The number and distribution of the survivors can be estimated before the burn. Success or failure can be judged rather quickly after a fire from crown condition of the trees.

Acknowledgements. Partial funding for this project was provided by the Georgia Forestry Commission. The USDI Fish and Wildlife Service, Piedmont National Wildlife Refuge provided the study areas and fire control backup during nine of the burns. Ted Ach conducted the burns and collected much of the data used under a contract with the USDA Forest Service, Southeastern Forest Research Station.

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